Quest Journals
Journal of Research in Mechanical Engineering
Volume 11 ~ Issue 4 (Jul. – Aug. 2025) pp: 08-13
ISSN(Online):2321-8185
www.questjournals.org

Research Paper

A Review of Powder Metallurgy-Based Fabrication of Ni–Ti Foams: Processing Routes, Structural Characteristics, and Functional Properties

Ajay Kumar Barnwal
Research Scholar, Department of Mechanical Engineering
Capital University, Koderma, Jharkhand

Dr. Hemant Jain, *Associate Professor*
Capital University, Koderma, Jharkhand

Dr. Parveen Kumar, *Associate Professor*
Guru Ghasidas Vishwavidyalaya, Bilaspur, Chhattisgarh

Abstract
The functional shape-memory alloy nickel–titanium (Ni–Ti), also referred to as nitinol, is distinguished by its shape-memory effect, superelasticity, corrosion resistance, good strength, damping capacity, and biocompatibility. Ni–Ti cellular structures with decreased density and elastic modulus are created by introducing controlled porosity while maintaining significant functional characteristics of the parent alloy. Ni–Ti foams are prospective for use in biomedical implants, energy absorption, vibration damping, aeronautical components, actuators, and multifunctional engineering applications because of their qualities. Because powder metallurgy offers relatively good control over composition, microstructure, pore morphology, and porosity, it has become one of the best methods for producing porous Ni–Ti.The theoretical underpinnings of powder metallurgy methods for the production of Ni–Ti foam are summarized in this review, with special attention paid to conventional sintering, space-holder processing, gas-entrapment techniques, self-propagating high-temperature synthesis, and sophisticated consolidation methods. Phase development and pore architecture are examined in relation to powder properties, Ni/Ti ratio, compaction, sintering temperature, atmosphere, and space-holder features. A critical analysis is conducted of the connections among porosity, pore morphology, microstructure, and mechanical behavior. Compressive strength, energy absorption, damping, shape-memory and superelastic behavior, and biological performance are all given special consideration. Additionally covered are the main issues related to fatigue, dimensional shrinkage, pore heterogeneity, oxygen contamination, secondary-phase development, and nickel release. According to the review, powder metallurgy offers a flexible platform for creating highly porous Ni–Ti with regulated linked structures, especially using the space-holder technique. Future advancements are anticipated to concentrate on surface modification, sophisticated sintering, computational design, architected and functionally graded foams, and better control over phase transformation and fatigue behavior.

Keywords: *Ni–Ti foam; Nitinol; powder metallurgy; space-holder technique; porous shape-memory alloy; sintering; porosity; superelasticity; biomedical applications.*

I. Introduction

Metallic foams are cellular materials where pores occupy a significant portion of the volume. Lightweight and multipurpose engineering materials are becoming more and more popular because to their low density, high specific strength, energy absorption capacity, damping behavior, and huge surface area. Nickel-titanium is a particularly appealing shape-memory alloy because it combines the benefits of cellular structures with the special functional characteristics of shape-memory alloys. Reversible martensitic transformation in near-equiatomic Ni–Ti results in shape-memory behavior and, in the right circumstances, superelasticity. This alloy's effective elastic modulus and density can be significantly decreased while functional deformation mechanisms are preserved when porosity is added.

Because porous Ni–Ti can be more mechanically compatible with bone than thick metallic implants due to its reduced stiffness, it has garnered significant interest in biomedical engineering. Additionally, biological fluid transfer and tissue ingrowth can be facilitated by interconnected holes. Additionally, porous Ni–Ti's large specific surface area benefits implant–tissue contact. Ni–Ti foams have prospective uses in energy absorption, vibration control, damping, actuators, aeronautical structures, and adaptive engineering systems in addition to biomedical applications.

It is much harder to produce porous Ni–Ti than traditional aluminum or steel foams. While the functional characteristics of Ni–Ti are extremely sensitive to chemical composition, titanium has a considerable affinity for nitrogen and oxygen. Martensitic transition temperatures and functional responsiveness can be considerably altered by slight changes in the nickel-to-titanium ratio. Titanium's high melting temperature and reactivity make conventional melting methods difficult as well. The advancement of powder metallurgical methods has been aided by these constraints.

Because metallic particles can be crushed and consolidated without completely melting, powder metallurgy offers an appealing substitute. Both intentional use of a sacrificial space holder and natural partial densification can produce porosity. Additionally, the technique offers control over the microstructure, pore morphology, particle size, and content of the powder. Therefore, the combination of particle qualities, compaction, sintering, phase formation, pore evolution, and transformation behavior determines the final properties of Ni–Ti foam.

This review aims to give a succinct theoretical evaluation of powder metallurgy methods for the fabrication of Ni–Ti foam. The link between phase constitution, pore architecture, processing conditions, and functional qualities is given special consideration.

II. Theoretical Basis of Powder Metallurgy Processing

Ni–Ti foam is typically produced by powder metallurgy using either pre-alloyed Ni–Ti powder or a combination of elemental nickel and titanium powders. While elemental powders can react during sintering to generate Ni–Ti, pre-alloyed powder provides greater control over the initial composition. From a processing standpoint, the elemental method is appealing, but it necessitates significant interdiffusion and can result in intermediary phases like $NiTi_2$ and Ni_3Ti. The local composition and temperature history play a major role in the creation of these stages. Packing, compaction, diffusion, and ultimate porosity are all significantly impacted by the size and shape of powder particles. Due to their wide contact area and low diffusion distances, fine particles can facilitate phase formation and sintering. However, because of their comparatively large surface area, fine titanium particles are more prone to oxidation. Although they can result in bigger interparticle gaps and slower diffusion, coarser powders lessen the relative impact of surface contamination. Therefore, to balance packing density, reaction kinetics, and contamination, a proper particle-size distribution is needed.

The powder mixture becomes a cohesive green body through compaction. Large spaces are first reduced by particle rearrangement, which is followed by plastic deformation and increased particle interaction. The ultimate pore structure is significantly influenced by the ensuing green density. The volume fraction, size, and shape of a space holder also affect the compaction reaction. Differences in the mechanical characteristics of space-holder particles and metallic powders might result in local density differences that eventually develop into pore heterogeneity. Atomic diffusion reduces surface and interfacial energy, which controls sintering. Diffusion increases structural integrity by forming and expanding interparticle necks during heating. Sintering of elemental Ni/Ti combinations is accompanied by intermetallic formation and chemical reactions. For the final NiTi phase to offer dependable shape-memory and superelastic capabilities, it must be sufficiently homogenous.

In particular, the processing environment is crucial. Because titanium is extremely reactive with carbon, nitrogen, and oxygen, contamination can change phase transformation behavior and decrease ductility. For this reason, high-purity inert atmospheres or vacuum are ideal. Oxide coatings on the initial powder particles may persist even in controlled environments and affect phase formation and diffusion.

III. Space-Holder Powder Metallurgy Technique

One of the best powder metallurgy methods for creating very porous Ni–Ti is the space-holder approach. This method involves mixing a temporary material with Ni and Ti or Ni–Ti powder prior to compaction. The volume that eventually becomes the pore network is occupied by the transient phase. The space holder is eliminated by dissolution, evaporation, decomposition, or melting after compaction, leaving a porous metallic framework that is then sintered.

The ability to regulate pore size and total porosity more independently than in traditional sintering is this technique's main advantage. The macroporosity is mostly determined by the volume fraction of the space holder, and the dimensions and geometry of the pores are influenced by its particle size and morphology. As a result, the technique is especially well suited for biological applications where pore size and interconnectivity are crucial.

Due to its low cost and ease of removal, sodium chloride has drawn a lot of interest as a space holder. Highly porous Ni–Ti foams, including structures with roughly 69% porosity, have been shown in studies utilizing NaCl. These structures have shown useful mechanical and functional properties together with interconnected pore networks. Ammonium bicarbonate, carbamide, magnesium, and polymeric compounds are among the other space holders that have been studied.

The space holder's distribution is crucial. The resulting foam may have areas with weak struts and high porosity if particles separate during mixing or compaction. On the other hand, a reasonably dense structure with little biological or fluid-transport benefits results from an inadequate space-holder content. Stress concentration is also influenced by the space holder's particle size. While angular particles may provide stronger geometrical characteristics and localized stresses, rounded particles often yield smoother pores.

Thus, the space-holder strategy offers a potent way to construct the Ni–Ti cellular architecture. However, maintaining the consistency of the space-holder distribution and avoiding contamination during removal continue to be significant obstacles.

IV. Conventional Sintering and Reactive Synthesis

Through partial densification, porous Ni–Ti can be produced by conventional pressureless sintering. This method involves compacting and heating the metallic powder in a controlled environment. While some pores stay inside the framework, diffusion encourages interparticle bonding. The pore size and connectivity cannot be regulated as independently as in the space-holder approach since they are mostly dictated by powder packing and sintering kinetics, despite the method's relative simplicity.

A series of chemical reactions occur during sintering when elemental Ni and Ti particles are utilized. Before the composition approaches NiTi, intermediate intermetallic phases may occur as a result of the initial reaction between nickel and titanium at particle surfaces. The initial Ni/Ti ratio, particle size, heating rate, sintering temperature, and holding duration all have a significant impact on the final phase constitution.

Another method for reactive powder metallurgy is self-propagating high-temperature synthesis. An exothermic reaction between titanium and nickel in SHS generates enough heat to spread the process throughout the compact. The method may quickly generate NiTi while lowering the need for external energy. Temperature gradients, incomplete reactions, secondary phases, and diverse pore architectures are possible outcomes of the quick reaction. These issues are especially significant for functional NiTi foam since secondary phases could negatively impact mechanical performance and martensitic transformation.

V. Advanced Powder Metallurgy Routes

By applying strong and constant pressure, hot isostatic pressing creates a very homogenous metallic skeleton during thermal consolidation. Although normal HIP is mostly used for densification, specialized methods can be used for porous constructions. The primary advantages are decreased density gradients and improved interparticle bonding. The disadvantages include rather complex procedures and high equipment expenses.

Metal injection molding is another powder metallurgy technique that can be applied to precisely produced porous Ni–Ti components. Fine particles are mixed with a polymeric binder, produced by injection molding, debound, and sintered. The technique offers a lot of geometric flexibility, but contamination and binder removal need to be carefully managed. Carbon and oxygen supplied during debinding may be particularly harmful to NiTi because they may alter phase change and mechanical characteristics.

Recent developments have also integrated powder metallurgy and additive manufacturing. Instead of relying just on random porosity, customized cellular forms can be created using digitally controlled structures. Lattice architectures and functionally graded porosity provide opportunities to simultaneously improve stiffness, strength, permeability, and energy absorption. These techniques represent a substantial change from conventional random foams to engineered NiTi cellular compositions.

VI. Microstructure and Phase Formation

The interplay of powder transport, sintering, chemical reaction, and pore formation significantly influences the microstructure of powder metallurgy Ni–Ti foam. Nickel and titanium interdiffuse to form the required NiTi phase in elemental powder systems. Secondary phases could persist if the composition is not uniform. While $NiTi_2$ can form in Ti-rich places, Ni_3Ti often occurs in Ni-rich regions.

These secondary phases have differing mechanical and transformation properties from NiTi, which makes them unattractive in applications requiring excellent functional performance. Fracture resistance may also be diminished by the existence of brittle intermetallic areas. As a result, it is crucial to precisely manage the initial powder composition and thermal treatment.

Another crucial microstructural factor is grain size. While excessive grain growth during high-temperature sintering can lower mechanical performance, fine grains can boost strength and affect

transformation behavior. Because pore surfaces can serve as barriers that limit grain mobility, the existence of pores further alters grain growth. As a result, the final microstructure is a complicated mixture of pore surfaces, oxide layers, phase barriers, and grains.

VII. Porosity, Pore Morphology and Mechanical Properties

The main structural factor controlling the mechanical behavior of Ni–Ti foam is porosity. Increasing porosity lowers the load-bearing cross-sectional area while simultaneously decreasing density and effective elastic modulus. According to cellular-solid theory, the effective modulus and relative density roughly follow a power-law relationship:

$\frac{E^*}{E_S} = C_E \left(\frac{\rho^*}{\rho_S}\right)^n$

Where

E^* = effective Young's modulus of the cellular solid

E_S =Young's modulus of the solid material from which the foam is made

ρ^* =density of the cellular solid

ρ_S =density of the fully dense solid

n= power-law exponent, typically **about 2 for bending-dominated open-cell foams**

C_E = empirical constant depending on cell morphology and deformation mechanism

For compressive strength, the relationship is similar. However, due of uneven pores, non-uniform struts, flaws, grain structure, and martensitic transformation, real Ni–Ti foams differ from ideal cellular-solid models.

Ni–Ti foams often show an initial elastic response, increasing collapse, and densification under compression. For energy absorption, the collapse region is especially crucial. However, Ni–Ti can also release energy through stress-induced martensitic transition, in contrast to traditional metallic foams. Ni–Ti foams have a unique mechanical response due to this mix of cellular deformation and transformation.

The absorbed energy can be expressed as

$W = \int_0^{\epsilon_D} \sigma(\epsilon) d\varepsilon$

Where W= absorbed energy per unit volume (MJ/m^3)

σ = compressive stress

ϵ_D = densification strain or specified maximum strain.

High porosity may reduce strength but can increase the strain range available for deformation. The optimum structure therefore depends on whether the primary requirement is lightweight construction, energy absorption, damping, or biomedical compatibility.

VIII. Shape-Memory and Superelastic Properties

The functional behavior of Ni–Ti foam is significantly influenced by reversible martensitic transformation. When heated in the shape-memory state, the reverse transformation enables the recovery of deformation introduced in the martensitic phase. In the superelastic state, stress induces martensitic transformation; however, unloading produces the reverse transformation without requiring an additional heating cycle.

Porosity modifies the distribution of stress within the material. In individual struts, bending, compression, tension, and shear can all happen at the same time, causing transformation to start at different places. This heterogeneous transition may lead to a broader mechanical reaction and increased energy dissipation.

Maintaining functional characteristics after powder processing is largely dependent on composition and phase purity. Secondary phases, oxygen pollution, residual stresses, and excessive grain growth can all change transformation temperatures or reduce recoverability. Therefore, in order to create NiTi foam, cellular architecture and metallurgical quality must be managed concurrently.

IX. Biomedical Applications

One of the most potential uses of porous Ni–Ti is biomedical implantation. Stress shielding is possible because dense metallic implants are typically more rigid than bone. By adding porosity, the effective stiffness is decreased and a more advantageous mechanical environment may be created.

Because they enable biological fluids and cells to enter the implant, interconnected holes are very crucial. Tissue adhesion may be enhanced by the larger surface area. Because the space-holder properties allow for the regulation of pore size and porosity, space-holder powder metallurgy is therefore very appealing for biomedical NiTi.

However, mechanical compatibility is not enough for biological applications. It is necessary to take into account long-term corrosion, nickel release, wear, fatigue, sterilization, and biological reaction. Therefore,

to enhance the biological performance of porous NiTi, surface modification and protective coatings would be necessary.

X. Energy Absorption and Damping Applications

Because of their huge deformation capacity and extra energy dissipation provided by martensitic transformation, Ni–Ti foams have great promise as energy absorbers. Vibration control, automotive, aerospace, and protective applications can all benefit from the combination.

Another crucial feature is damping. Phase transformation and the movement and deformation of the cellular network both result in the dissipation of energy. Significant dampening behavior has been discovered in studies of porous NiTi, suggesting possible uses in adaptive structures and vibration isolation.

Cyclic durability is the primary constraint. After repeated transformation and mechanical loads, a material with good single-cycle energy absorption may undergo functional deterioration. Therefore, steady transformation behavior and fatigue-resistant pore designs must be the main areas of future research.

XI. Current Challenges and Future Prospects

Despite tremendous advancements, a number of obstacles still prevent powder metallurgy Ni–Ti foams from being used more widely. Because titanium reacts easily with oxygen during powder handling and sintering, oxygen contamination is still a significant issue. Phase constitution and transformation temperatures can also be greatly impacted by little variations in Ni/Ti composition.

Another significant restriction is pore heterogeneity. Localized stress concentration and areas of weak struts can be produced by variations in green density and space-holder distribution. Under cyclic loads, these flaws become very significant. Thus, three-dimensional characterisation, controlled compaction, and improved powder mixing are needed.

It is anticipated that future studies will focus on functionally graded and hierarchical NiTi foams. Instead of creating a homogeneous pore structure, scientists can create spatial variations in porosity to serve distinct mechanical or biological purposes in various parts of a component. Even more control over cellular architecture could be made possible via computational design and additive manufacturing.

Grain growth may be inhibited and phase control enhanced by sophisticated sintering techniques such microwave-assisted sintering, spark plasma sintering, and tailored fast thermal processing. Predicting the link between processing conditions, pore architecture, and functional qualities may also be made easier with the help of computational modeling and machine learning.

XII. Conclusion

A very flexible method for creating Ni–Ti foams with regulated porosity and useful mechanical behavior is powder metallurgy. Because NiTi is challenging to produce using traditional melting techniques and because its shape-memory and superelastic qualities are extremely sensitive to composition and microstructure, the approach is especially valuable.

The most direct way to control linked porosity and pore morphology is through space-holder powder metallurgy. Highly porous structures appropriate for biological and energy-absorption purposes can be produced using sodium chloride and other detachable space holders. While SHS, HIP, metal injection molding, and advanced powder-based production offer alternate methodologies with distinct advantages and limits, conventional sintering offers simplicity but very restricted pore control.

The interplay of porosity, pore morphology, phase constitution, grain structure, and martensitic transformation determines the final performance of NiTi foam. While stiffness and density can be decreased by increasing porosity, strength and fatigue resistance may also be compromised. Therefore, optimizing rather than just boosting porosity is necessary for successful NiTi foam design.

Future studies should focus on surface modification, fatigue resistance, pore homogeneity, phase stability, oxygen management, and architected cellular structures. A new generation of NiTi foams with regulated mechanical, functional, and biological properties is anticipated by the combination of powder metallurgy, sophisticated production, and computational design. NiTi foams generated from powder metallurgy have significant promise for use in energy absorbers, dampening systems, sophisticated biomedical implants, and multipurpose lightweight structures with further development.

References

[1]. Banhart, J. (2001). Manufacture, characterisation and application of cellular metals and metal foams. *Progress in Materials Science, 46*, 559–632.
[2]. Banhart, J. (2006). Metal foams—Challenges and opportunities. *Europhysics News, 37*, 17–20.
[3]. Bansiddhi, A., & Dunand, D. C. (2008). Shape-memory NiTi foams produced by replication of NaCl space-holders. *Acta Biomaterialia, 4*, 1996–2007.

[4]. Bansiddhi, A., Sargeant, T. D., Stupp, S. I., & Dunand, D. C. (2008). Porous NiTi for bone implants: A review. *Acta Biomaterialia, 4*, 773–782.
[5]. Baranwal, A. K., Mondal, D. P., & Kumar, R. Recent studies on Ni–Ti alloy foams fabricated through powder metallurgy using NaCl as a space holder. *Advanced Materials Letters*.
[6]. Gibson, L. J., & Ashby, M. F. (1997). *Cellular Solids: Structure and Properties*. Cambridge University Press.
[7]. Dunand, D. C. (2004). Processing of titanium foams. *Advanced Engineering Materials, 6*, 369–376.
[8]. Erk, K. A., & Dunand, D. C. Studies on porous NiTi shape-memory alloys and their mechanical properties.
[9]. Li, B. Y., Rong, L. J., Li, Y. Y., & Gjunter, V. E. (2000). A recent development in producing porous NiTi shape-memory alloys. *Materials Science and Engineering A*.
[10]. Li, B. Y., Rong, L. J., & Li, Y. Y. (2000). Porous NiTi alloy prepared from elemental powders by self-propagating high-temperature synthesis. *Materials Science and Engineering A*.
[11]. Parvizi, S., Hashemi, M., Asgarinia, F., et al. (2021). Effective parameters on the final properties of NiTi-based alloys manufactured by powder metallurgy methods: A review. *Progress in Materials Science, 117*, 100739.
[12]. Wen, C. E., Yamada, Y., Shimojima, K., Chino, Y., Hosokawa, H., & Mabuchi, M. (2002). Compressibility of porous titanium foam. *Journal of Materials Research*.
[13]. Zhao, Y., Taya, M., Kang, Y. S., & Kawasaki, A. Studies on compression and shape-memory behavior of porous NiTi alloys.
[14]. Ashby, M. F. (2006). The properties of foams and lattices. *Philosophical Transactions of the Royal Society A, 364*, 15–30.
[15]. Ashby, M. F., Evans, A. G., Fleck, N. A., Gibson, L. J., Hutchinson, J. W., & Wadley, H. N. G. (2000). *Metal Foams: A Design Guide*. Butterworth-Heinemann.